

# IEEE 802.11az Indoor Positioning with mmWave

Pablo Picazo-Martinez, Carlos Barroso-Fernández, Jorge Martín-Pérez,  
Milan Groshev and Antonio de la Oliva

**Abstract**—Last years we have witnessed the uprising of location based applications, which depend on the devices ability to accurately obtain their position. IEEE 802.11, foretelling the need for such applications, started the IEEE 802.11az work on Next Generation Positioning. Although this standard provides positioning enhancements for sub-6 GHz and mmWave bands, high accuracy in the order of centimeters can only be obtained in the latter band, thanks to the beamforming information available at mmWave operation. This work presents a detailed analysis on the new techniques provided by IEEE 802.11az for enhanced secured positioning in the mmWave band, assessing them through experimentation.

**Index Terms**—IEEE 802.11 standard, Next Generation Positioning, FTM, EDMG, mmWave

## I. INTRODUCTION

With the advance of new applications as presence detection, activity recognition, human target localization and tracking, 3D vision, and healthcare; localization and positioning features are demanded from local and personal wireless technologies. In addition, accurate positioning is also essential for the manufacturing industry to ensure that machinery, robots, and equipment are operating correctly; hence preventing accidents and reducing downtime. To meet these demands, the IEEE 802.11az Task Group (802.11az for short) worked since 2015 to 2022 on an amendment [1] that defines PHY and MAC updates for Next Generation Positioning.

The authors are with the Department of Telematics Engineering, Universidad Carlos III de Madrid; and Departamento de Ingeniería de Sistemas Telemáticos, Universidad Politécnica de Madrid. E-mail: {papicazo,cbarroso,mgroshev}@pa.uc3m.es, jorge.martin.perez@upm.es, aoliva@it.uc3m.es.

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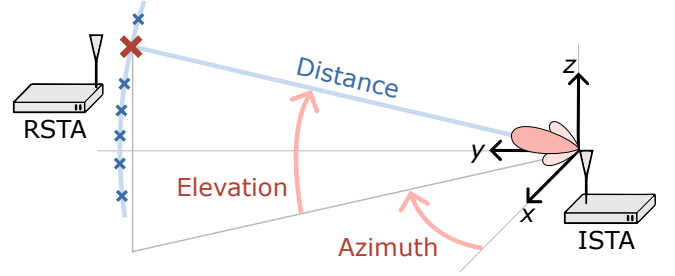


Fig. 1. Legacy positioning in 802.11 only knew the distance between devices, thus, there are many feasible locations (blue markers). 802.11az uses mmWave beamforming to obtain the azimuth and elevation between devices, hence, the exact location (red marker).

Although 802.11az provides enhancements for sub-6 GHz and Millimeter Wave (mmWave) operation at 60 GHz, the best positioning accuracy is achieved in the latter band. Specifically, 802.11az obtains accurate positioning information using 802.11ay Enhanced Directional Multi-Gigabit (EDMG) beamforming [2], along with its accurate Channel State Information (CSI) reports. With the orientation of the mmWave beam and CSI reports, 802.11az elaborates angle estimations funded on the ranging accuracy of multi-GHz bandwidths.

Unlike Received Signal Strength Indicator (RSSI) based solutions [3], 802.11az combines mmWave-based angle estimations with the Time of Flight (ToF) to achieve high accuracy positioning. Both the ToF and angle estimations are exchanged using the Fine Timing Measurement (FTM) procedure – introduced in 802.11mc [4] –, and Station (STA)s use the exchanged estimations to determine the distance, azimuth and elevation between STAs – see Fig. 1.

Since mmWave promises to increase positioning accuracy from meter level [5] to centimeter-level [6], [7]; in this article we explain the main contributions of 802.11az for mmWave based positioning:

**FTM procedure over EDMG.** In the legacy FTM procedure STAs only exchange ToF estima-

tions, thus, obtaining just an approximation of the distance. 802.11az performs the FTM procedure over EDMG to also exchange angle estimations obtained through CSI reports. Namely, STAs exchange the angle at which the signals depart and arrive to the STA, i.e., the Angle Of Departure (AOD) and Angle Of Arrival (AOA). With the distance and angle estimations it is possible to obtain the exact position of a STA – see Fig. 1.<sup>1</sup>

**LOS assessment over the first path.** When STAs are not at Line Of Sight (LOS) it becomes challenging to obtain the position due to signal reflections, e.g., on walls. Thus, it is important to determine if STAs are at LOS to derive accurate position estimations. 802.11az introduces a LOS assessment procedure that tells if STAs are at LOS using dual polarization over first path transmissions. In case the LOS assessment succeeds it is possible to obtain the exact position of a STA as depicted in Fig. 1. Otherwise, signal reflections should be considered.

**Secure Next Generation Positioning.** Since FTM exchanges may be triggered without association, malicious STAs may derive users' position. To prevent that, 802.11az proposes a Pre-Association Security Negotiation (PASN) to exchange a key used to secure FTM sessions between not associated STAs. Moreover, 802.11az increases the location privacy with physical security randomizing the Training (TRN) subfields used in EDMG Physical Protocol Data Unit (PPDU)s. Hence, no third party can derive estimations about other STAs location.

The remainder of this article is as follows. Sec. II-IV detail the main contributions of 802.11az mmWave-based positioning. Next, Sec. V assesses the accuracy of future 802.11az mmWave-based implementations. Finally, Sec. VI identifies the existing challenges to be addressed while implementing mmWave-based 802.11az.

## II. FTM PROTOCOL OVER EDMG

802.11az exchanges positioning information using the FTM protocol. In this section we explain how 802.11az achieves Next Generation Positioning

using FTM over EDMG, so as the frames encapsulation, negotiation procedure and measurement exchange.

### A. Next Generation Positioning in FTM & EDMG

802.11az positioning is funded on knowing the distance, elevation and azimuth between STAs – see Fig. 1. While the distance is computed using the ToF of FTM exchanges, the azimuth and elevation angles are obtained using the mmWave beamforming procedure defined in 802.11ay EDMG.

In EDMG beamforming the station that initiates the FTM exchange (ISTA) tries different Antenna Weight Vector (AWV) configurations until the mmWave beam points to the Responding Station (RSTA). Namely, the Initiating Station (ISTA) chooses the AWV that gives highest quality in the associated channel measurements. Through this procedure, the orientation of every antenna in the array can be computed and the ISTA can estimate the AOD of the mmWave beam, i.e., the elevation and azimuth – see Fig. 1.

With the distance, elevation and azimuth estimations; the ISTA retrieves high accuracy relative positioning with respect to the RSTA. In case the STAs send Location Configuration Information (LCI) in the FTM exchanges, it is also possible to know the absolute positioning – for LCI and location reports include information such as latitude, longitude, or location within a building or GPS coordinates.

### B. FTM encapsulation in EDMG

FTM frames are encapsulated as 802.11 Action fields – see Fig. 2. If FTM is used between two EDMG STAs, the FTM frame is sent within an EDMG PPDU, which allows simultaneously to (i) derive positioning estimations using the EDMG TRN field; and (ii) exchange positioning estimations within the FTM frame.

The TRN field within the EDMG PPDU includes Golay sequences that have useful autocorrelation properties for channel measurements. In particular, channel measurements are obtained by comparing the received TRN field with the expected Golay sequence. The 802.11az amendment uses TRN-based channel measurements to perform positioning estimations as AOA/AOD and LOS assessments – as explained in Sec. III.

<sup>1</sup>Note that throughout the paper we use blue color for legacy features, purple color for legacy features that were extended in the IEEE 802.11az amendment and red color for new features.

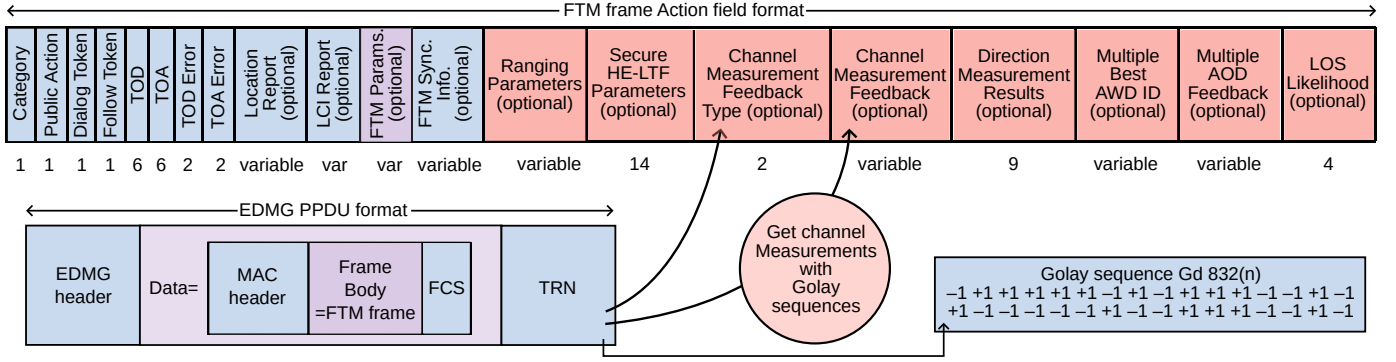


Fig. 2. FTM frames (top) are Action fields encapsulated in the MAC Frame Body inside EDMG PPDU (bottom left). The TRN field sends Golay sequences (bottom right) used for Channel Measurements included in the FTM frame. The figure shows FTM legacy fields (blue), so as 802.11az additions (red) and modifications (purple). Numbers below the FTM frame indicate the number of octets that each field occupy.

The channel and angle estimations obtained with TRN are carried in the encapsulated FTM frames. In particular, the 802.11az amendment has extended the FTM frames to carry the TRN Channel Measurements associated to the AWW, angle estimations, and LOS likelihood – see Fig. 2 red fields. These new fields are complemented with legacy timestamps, localization and synchronization information – blue color in Fig. 2 – to obtain accurate positioning.

### C. Negotiating FTM sessions over EDMG

To start an FTM session over EDMG, STAs have to negotiate parameters, such as the session duration or the number of FTM bursts within a session.

The negotiation starts with the exchange of an Initial FTM Request (IFTMR) where the ISTA proposes, e.g., an EDMG FTM session over the first path with one burst and AOD estimations – as in Fig. 3. Additionally, the ISTA may propose a secure exchange using a specific bandwidth between 2.16 and 8.64 GHz.

If the FTM session will go over the first path, the STAs should previously do a First Path Beam-forming Training (FPBT) – as illustrated in Fig. 3. Then, it is up to the RSTA to accept or not the proposed parameters for the new FTM session. In case the RSTA accepts the parameters of the received IFTMR, it sends an Acknowledgement (ACK) followed by an Initial FTM (IFTM) frame in less than 10 ms. In this last exchange, the RSTA may override some of the proposed parameters, e.g., to decrease the proposed session duration.

The negotiation fails in case the RSTA does not reply with an ACK or the IFTM frame reports

that the FTM session cannot start. Specifically, the session cannot start if the RSTA is not capable of satisfying the proposed parameters or it suffers an internal failure.

### D. FTM measurement exchange over EDMG

After a successful negotiation, STAs start an FTM session to perform distance and angle measurements. Each session consists of bursts with multiple exchanges of FTM frames encapsulated in EDMG PPDU. Fig. 3 illustrates an FTM session consisting of a single burst of three FTM and ACK exchanges, each one separated by Min Delta seconds.

In every exchange the STAs timestamp the Time of Departure (TOD) and Time of Arrival (TOA) of the sent and received frames, respectively. As a result, it is possible to estimate the distance in the first exchange by multiplying the speed of light by the corresponding Round Trip Time (RTT) ( $RTT_1$ ). Fig. 3 illustrates in blue boxes the timestamps used in the RTT estimation.

However, the real time at which frames depart and arrive may differ with the respective timestamps. For example, an IFTM frame may have departed at nanosecond 1 ns, whilst the clock timestamp may be  $t_{1\_1} = 1.1$  ns – thus, the TOD Error of 0.1 ns shown in Fig. 2. Due to the speed of light, the timestamp error of 0.1 ns would result in a distance estimation error of 3 cm. Hence, FTM should obtain distance estimations using the exchange whose timestamps had least error.

To derive angle estimations within a burst, the STAs compute channel measurements using the EDMG TRN fields. Additionally, STAs change their AWW during the session to try out multiple setups

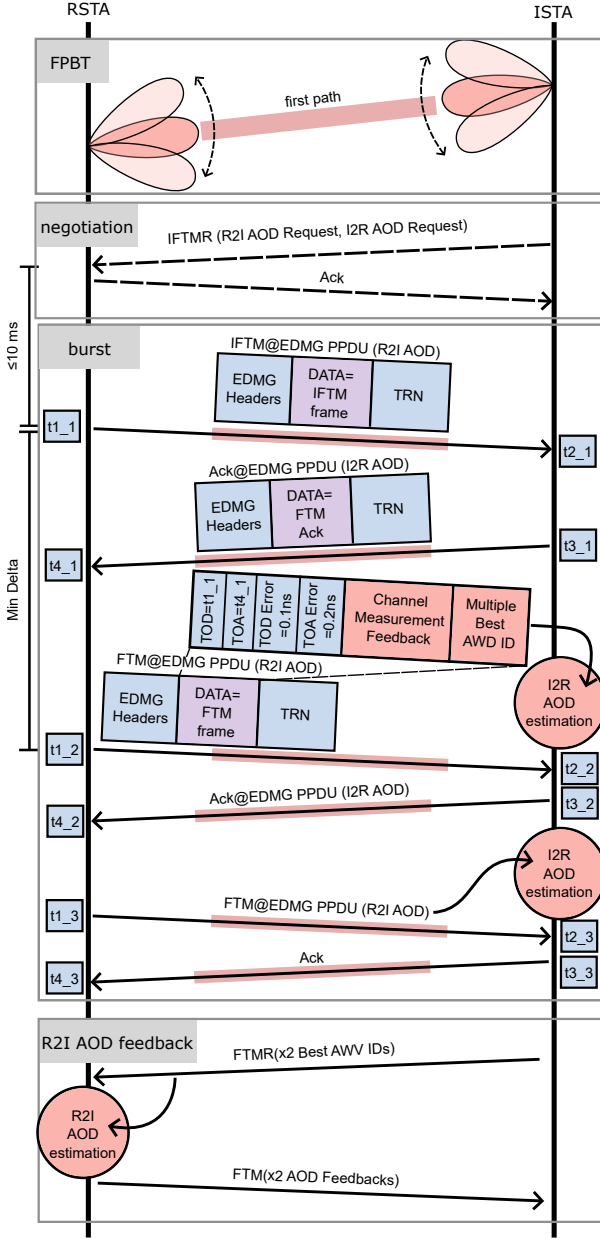


Fig. 3. FTM session over EDMG with FPBT, I2R and R2I AOD measurements. The illustration highlights legacy (blue), modified (purple), and new (red) features from 802.11az.

that may help in the angle estimation. Fig. 3 exemplifies how the initiator estimates the angle at which its signal departs using the channel measurements and best AWD reported by the responder in an FTM frame. The accuracy of the angle estimations is funded on the quality of the exchanged Channel Measurement Feedback – see the first I2R AOD estimation in Fig. 3.

In an FTM session it is possible to drive multiple Initiator-to-Responder (I2R) AOD estimations during the burst – two estimations in Fig. 3 ex-

ample. But in the case of Responder-to-Initiator (R2I) AOD, 802.11az specifies that the estimations are done once the burst finishes. Specifically, the initiator exchanges the best AWD setups perceived during the burst so the responder can estimate its AOD – see Fig. 3. Finally, the responder sends back to the initiator the two angle estimations.

### III. FPBT AND LOS ASSESSMENT

In this section we explain the FPBT and LOS assessment procedures. FPBT is a procedure used to identify the first path, also known as the propagation path, between two stations. Once the first path is identified, the LOS assessment determines if that path has direct line of sight or is a reflected path.

#### A. First Path Beamforming Training (FPBT)

In the FPBT procedure, the STAs try different mmWave antenna configurations until the beam points to the first path. In particular, the STAs sweep over multiple AWD configurations and select the best one – see Fig. 4 (left). In the following we detail the FPBT procedure presenting (i) the EDMG TRN fields; and (ii) the AWD sweep procedure.

The EDMG PPDU contains the TRN field that is used to perform channel estimations in the FPBT procedure. The TRN field contains  $L+1$  TRN-Units with TRN Subfields inside – see Fig. 4 (left). Every TRN-Unit contains  $P+M$  TRN Subfields that are filled with Golay sequences. The transmission of the Golay sequence inside the TRN Subfield results in a Power Delay Profile (PDP) that measures the in-phase, quadrature and Signal Noise Ratio (SNR) of each tap – see the PDPs of TRN Subfields  $P+1$  and  $P+2$  in Fig. 4 (left).

The AWD sweep procedure changes the mmWave antenna configuration looking for the first path. In particular, it changes the AWD after the transmission of a group of TRN Subfields – e.g., after a group of two in Fig. 4 (left). Then, the STA combines the PDPs of each TRN Subfield in the group, and selects the highest amplitude taps. The quality of the combined PDP is measured by checking the taps near the one with highest amplitude – see Fig. 4 (left). Finally, the STA compares the combined PDPs in the TRN field, and selects the best AWD – which points to the first path.

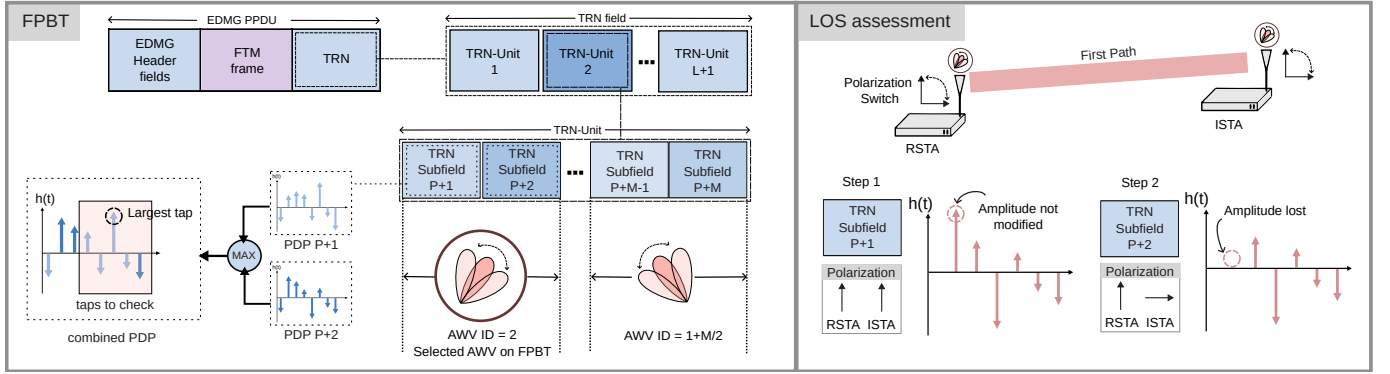


Fig. 4. 802.11az finds the first path sweeping the mmWave beam during the transmission of EDMG TRN Subfields (left). Then, STAs change their mmWave antenna polarization to tell whether they are at LOS (right).

### B. Line Of Sight (LOS) Assessment

Once FPBT determines the best AWV, the ISTA initiates an FTM LOS assessment exchange. In the exchange the STAs alternate the antenna polarization to determine whether the first path is at LOS. As STAs change the antenna polarization, they elaborate LOS Likelihood reports included in the FTM frames – see Fig. 2 last field. LOS assessment is performed as follows.

First, STAs transmit and receive using the same antenna polarization for the TRN Subfield P+1. If STAs are at LOS the amplitude of the main tap is not modified – see Fig. 4 (right). Second, the ISTA transmits the TRN Subfield P+2 with horizontal polarization, while the RSTA receives it with vertical polarization. As a result, the amplitude of the main tap is lost in the reception of the TRN Subfield P+2 due to polarization mismatch. Consequently, the STAs are at LOS, since main tap amplitude would not be lost if there is a reflection.

## IV. SECURE NEXT-GENERATION POSITIONING

With 802.11az it is possible to achieve security in the FTM exchange even among non-associated STAs by using the PASN procedure to secure the FTM session.

### A. Pre-Association Security Negotiation (PASN)

PASN is a protocol which reaches a Pairwise Transient Key Security Association (PTKSA) between and Access Point (AP) and a STA without previous association. In this situation, PASN acts

as a Robust Security Network Association (RSNA) protocol.<sup>2</sup>

To obtain the PTKSA key the STA and AP exchange three PASN elements (inside authentication frames) – see Fig. 5. First, the STA sends to the AP an ephemeral key and parameters to later derive a PMK. Second, the AP sends to the STA a protected frame with its ephemeral key and the chosen parameters to derive the PMK. Third, the STA confirms the chosen parameters sending an ACK within a protected frame.

Upon confirmation, the STA and AP use the Key Derivation Function (KDF) to generate the PTKSA key using the parameters negotiated in the exchanged PASN frames.

### B. Secure FTM sessions

After the STA and AP reach a PTKSA, the latter requests a Secure FTM session issuing an Initial Protected FTM Request (IPFTMR) – see Fig. 5. Then, the STA and AP obtain their relative position exchanging EDMG secure ranging PPDUs. The exchanged PPDUs contain Protected FTM (PFTM) frames and secure TRN Subfields for channel and positioning estimations. To achieve security, the TRN Subfields and PFTM frames are cyphered as follows.

The PFTM frame is cyphered using the PTKSA. While the secure TRN Subfields are filled with padded pseudorandom bit sequences generated in two steps. First, the STA creates a Pseudo-random Key (PRK) using an SHA-256 hash function that receives the Secret Key and the identifier of the

<sup>2</sup>PASN can also reach the PTKSA without the Pairwise Master Key (PMK), acting as a non-RSNA protocol.



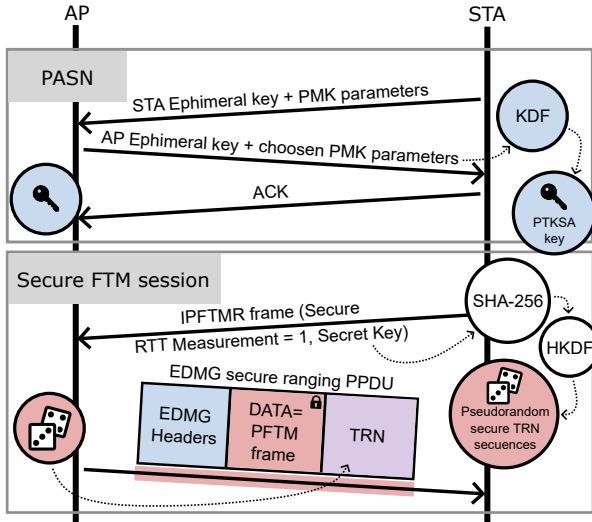


Fig. 5. The STA and AP securely pre-associate using 802.11az PASN (top). Afterwards, both protect the FTM session (bottom) cyphering the FTM frame (black lock), and generating pseudorandom secure TRN sequences at PHY level (dice).

PMK previously generated, e.g., in PASN. Second, the STA produces the pseudorandom secure TRN sequence by feeding the HMAC-based Key Derivation Function (HKDF) with (i) the PRK; (ii) the string “EDMG Secure RTT”; and (iii) the length of the TRN field.

## V. EXPERIMENTAL ANALYSIS

In this section we evaluate the potential position accuracy of future mmWave-based implementations of 802.11az. For the experimental analysis we use commercial MikroTik AP 60G devices with mmWave antennas, legacy 802.11mc FTM, and OpenWrt. The enhancements provided by 802.11az are assessed combining RTT estimations of legacy FTM, and angle estimations provided by a customized version of OpenWrt [8].

We assess the positioning accuracy in LOS and Non Line Of Sight (NLOS) scenarios. In the LOS scenario STAs are located to be at LOS, whilst in the NLOS scenario STAs are separated by a wall, thus, the signal has to reflect with 60° to reach the other STA – see Fig. 6 (top). In both scenarios the signal has to travel 2 m, 4 m, and 8 m; regardless the STAs are at LOS or NLOS.

In the experimental analysis we assume that both STAs have performed FPBT prior to the FTM exchange. However, commercial devices have not yet implemented the 802.11az FPBT. Therefore, we face the STAs antennas to be at LOS with

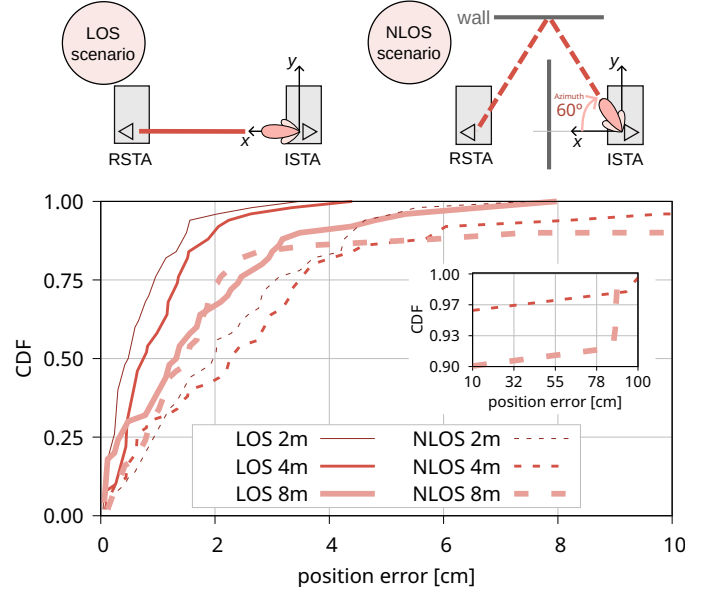


Fig. 6. Position error (bottom) using mmWave devices at LOS and NLOS (top). During the experiment the propagation path increases from 2 m (thin line) up to 4 m (medium) and 8 m (thick line). Scenarios are illustrated (top) in zenithal perspective.

0° azimuth an elevation (LOS scenario), and at NLOS with 60° azimuth and 0° of elevation (NLOS scenario). To check that the antennas are oriented adequately we check the AOA reported by the hacked version of OpenWrt [8].

Once the STAs are oriented adequately, we issue 50 legacy FTM sessions to obtain RTT estimations. Afterwards, we compute offline the relative position using the RTT estimation and AOA of the LOS/NLOS scenarios, i.e., using azimuths of 0° and 60°; respectively. As a result, we derive the position error by comparing the estimated position with the real position of the STAs.

Fig. 6 (bottom) illustrates the position error Cumulative distribution function (CDF) in the LOS (solid) and NLOS (dashed) scenarios. Results evidence that in the LOS scenario the position error increases with the distance between STAs, always preserving an error below 8 cm. In the NLOS scenario, the 90<sup>th</sup>-percentile position error remains below 10 cm, and only goes up to 100 cm in 10% of the runs – see Fig. 6 inset. Interestingly, the 75<sup>th</sup>-percentile position error of the NLOS scenario remains the lowest when the STAs are at 8 m distance. The phenomena is explained due to the presence of multipath components in the reflection [9], which harness the positioning accuracy.

## VI. CHALLENGES

The experimental analysis from the prior Section evidence promising positioning precision in upcoming 802.11az implementations. During experiments we have identified several challenges that vendors will have to tackle implementing 802.11az mmWave positioning:

- 1) **Mitigate the multipath effect.** When devices are at NLOS the positioning error increases due to the presence of multipath components [9] in the mmWave channel – see Fig. 6 dashed lines. Although 802.11az mitigates the problem using Single Carrier Orthogonal Frequency-Division Multiplexing (SC-OFDM) and Golay sequences, multipath components will remain. Vendors could consider additional solutions [8] that also use the sub-6 GHz channel to mitigate the multipath problem.
- 2) **Minimize energy consumption and reduce overheating.** 802.11az devices using mmWave are highly demanding in terms of energy consumption due to: the inherent higher power consumption of mmWave, the high clocking rate required and the execution of vendor-specific positioning algorithms. Vendors will have to design energy efficient chipsets to avoid draining the device battery and reduce overheating.
- 3) **Improve accurate secure positioning.** As explained in Sec. IV, secure TRN sub-fields use padded pseudorandom bit sequences rather than Golay sequences. Consequently, the channel measurements will not be as precise and detriment the positioning accuracy. Vendors may overcome the limitation using Golay sequences cyphered with homeomorphisms [10] that preserve the autocorrelation properties.

## VII. CONCLUSION

In this paper we overview the main features of the 802.11az to obtain next generation positioning through mmWave. The new amendment enhances the legacy FTM positioning accuracy with angle estimations obtained through mmWave beamforming. Additionally, the amendment introduces a secure pre-association procedure, and secure FTM sessions. Through experimental analysis we

show that mmWave 802.11az implementations will achieve positioning errors below 10 cm. Additionally, we identify challenges encountered assessing the 802.11az positioning with mmWave.

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**Pablo Picazo-Martínez** got his M.Sc. in 2022 and is a Ph.D. student at Universidad Carlos III de Madrid.

**Carlos Barroso-Fernández** got his M.Sc. in 2022 and is a Ph.D. student at Universidad Carlos III de Madrid.

**Jorge Martín-Pérez** got his M.Sc. in 2017 and Ph.D. in 2021, is an assistant professor at Universidad Politécnica de Madrid.

**Milan Groshev** got his Ph.D. on Telematics Engineering in 2022 at Universidad Carlos III de Madrid, where he works as postdoc.

**Antonio de la Oliva** got his M.Sc. in 2004 and his Ph.D. in 2008, is an associate professor at Universidad Carlos III de Madrid.